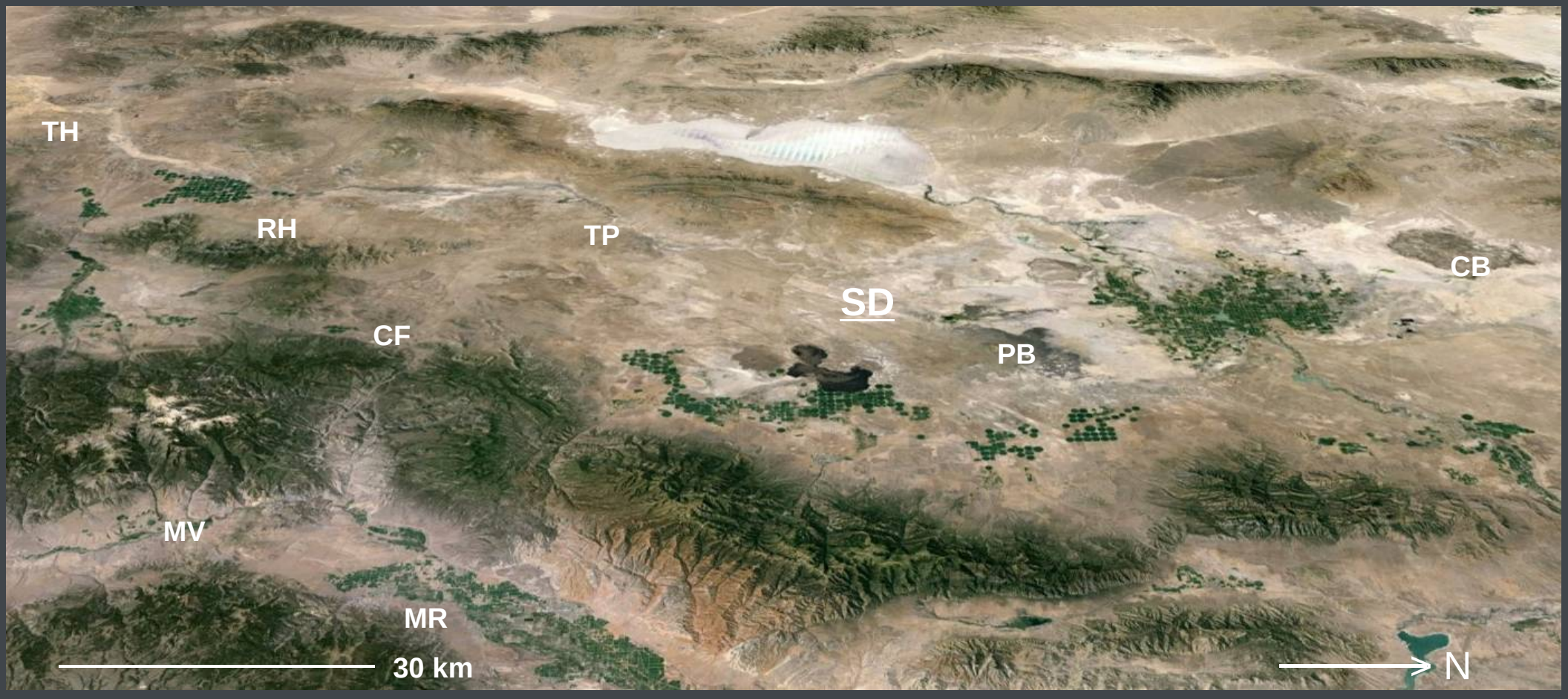

Play Fairway Analysis (PFA): Structurally Controlled Geothermal Systems in the Eastern Great Basin Extensional Regime, Utah

Project Officer: Michael Weathers; Total Project Funding: $1,679,438

Contract DE-EE0006732

Nov 15, 2017

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Track 2: Play Fairway Analysis

This presentation does not contain any proprietary confidential, or otherwise restricted information.

Co-I's: Kristine Pankow (U UT/GG); Joseph Moore, Gregory Nash, Stuart Simmons (U UT/EGI)

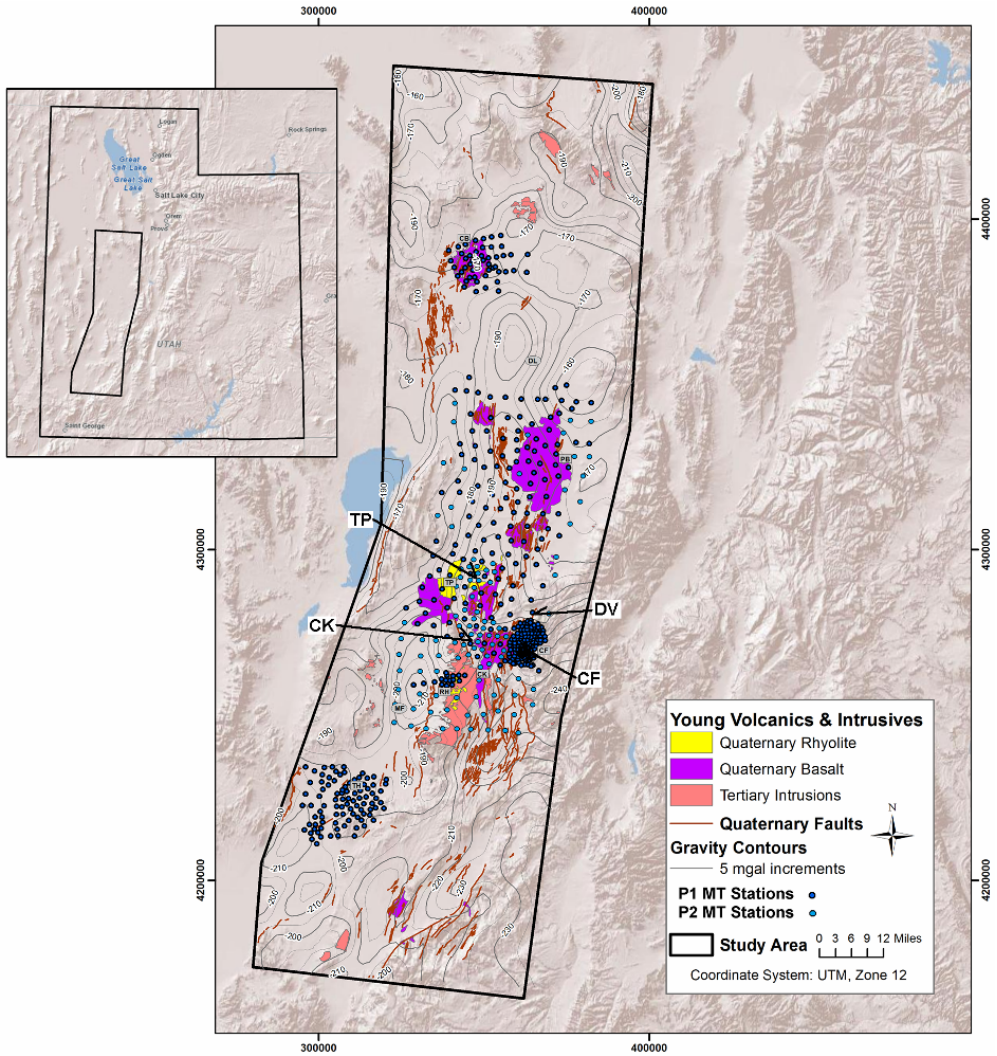
Relevance/Impact of Research

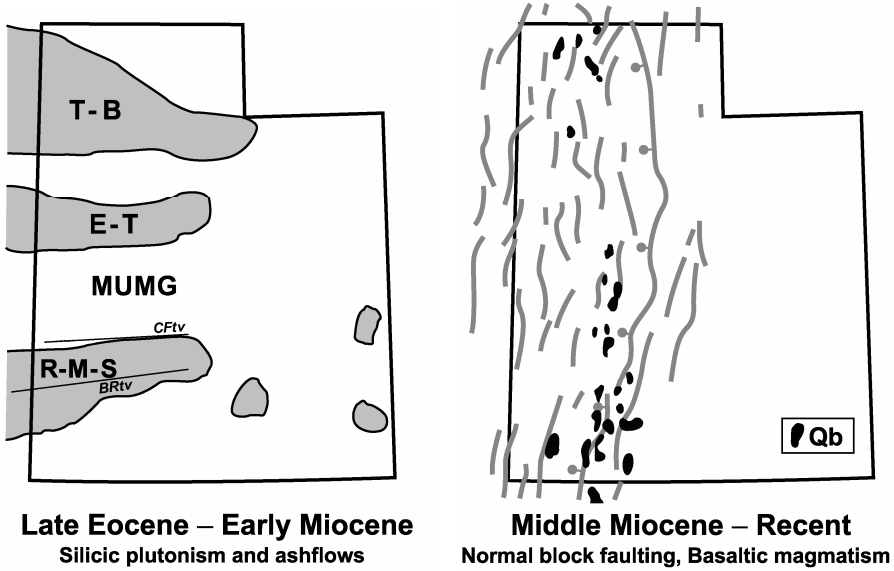
- Principal Objective: Accelerate Near-Term Hydrothermal Growth
  - Lower risks and costs of development and exploration
  - Lower levelized cost of electricity (LCOE) to 6 cents/kWh by 2020
  - Accelerate development of 30 GWe undiscovered hydrothermal resources

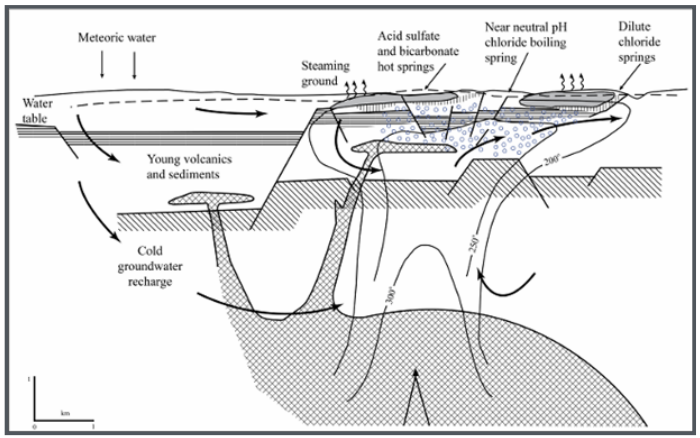
- *Challenges/Knowledge Gaps*: Develop a Play Fairway Analysis (PFA) model for Eastern Great Basin, Utah; apply rigorous 3D analysis of diverse data sets; identify permeability and deep fluid sources.
- *Cost Impact*: Improved geothermal costs through new methodologies, new geothermal play model, economies of scale.
- *Innovative Aspects*: Combines unusually large MT and seismicity data sets, dilatent structural analysis, spring and well geochemistry; new 3D MT inversion method; unusually good high-T system potential.
- *Meeting GTO goals*: Intended to open an underdeveloped U.S. geothermal province; identify new plays and play types.

Scientific/Technical Approach

- Eastern Great Basin Rationale: Superposition of modern N-S striking rift axis and magmatism across E-W structural/plutonic trends promoting dilatency.



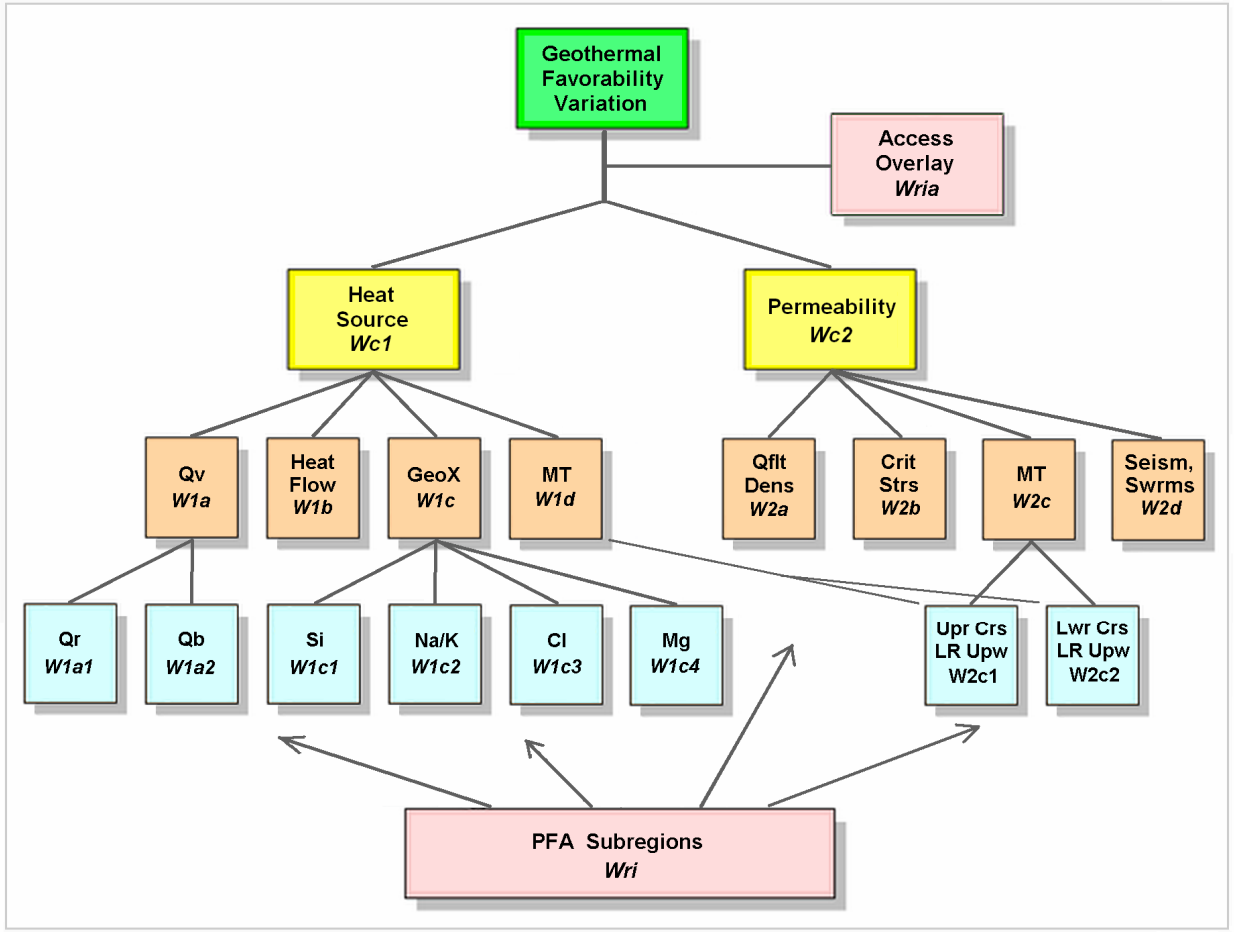




Conceptual Silicic System
(after Henley and Ellis, 1983)

Scientific/Technical Approach

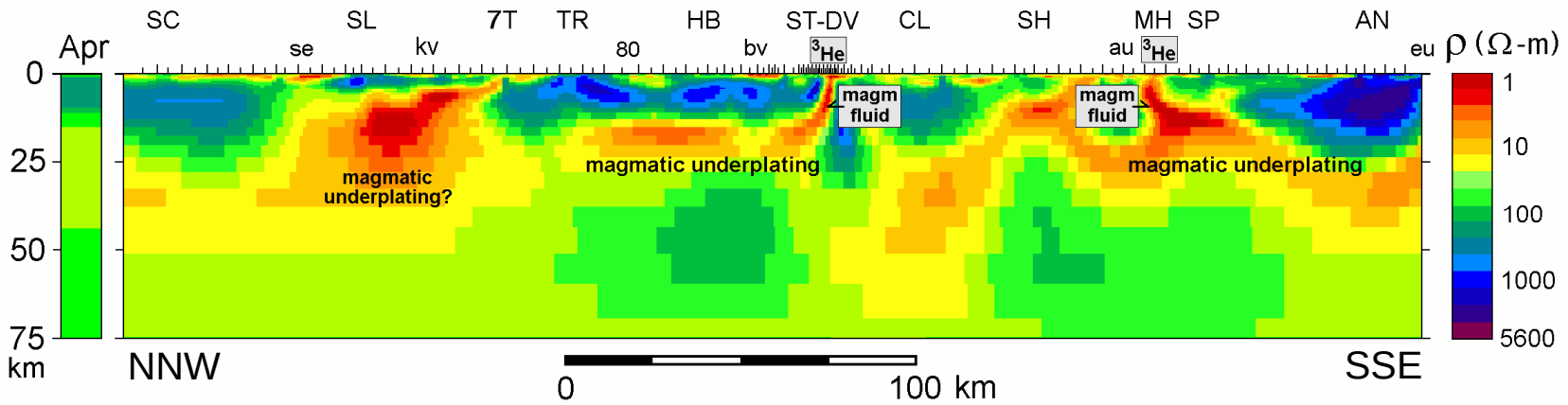
- PFA Approach Summary: Need to identify heat source, access to fluids, pathways to heat up and concentrate fluids, high permeability reservoir, caprock.
- Use MT to image high-T, fluidized upwellings; Test possible deep fluid zones with seismic swarms; Mapping and high-res geomorphology for structural modeling; Major element and isotope interpretation for subsurface and fluid X-T state; Rasterized favorability map.



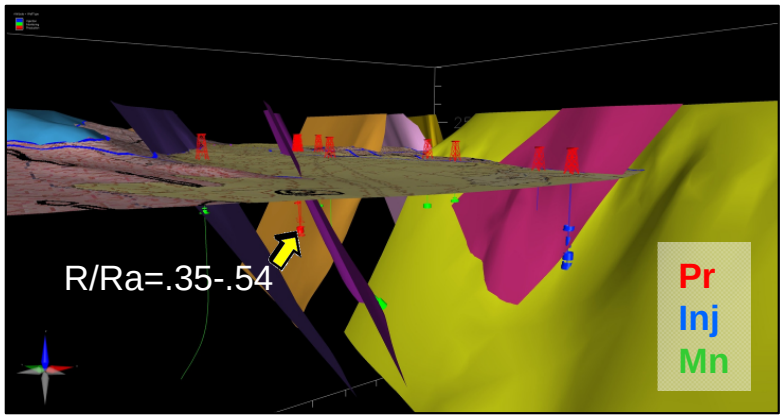
Multi-Criteria Decision Making (MCDM) Template

Approach

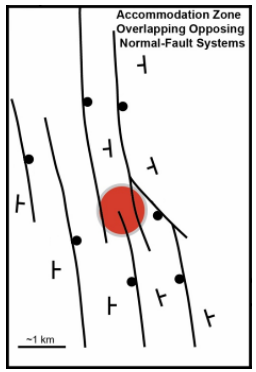
Great Basin Magmatism & McGinness Hills System
Motivation for Method Integration in Eastern Great Basin



- Structural setting as accommodation zone
- Deep magmatic connection from elevated R/Ra
- CO_2 flux anomaly along ~NW fault zone



⇦

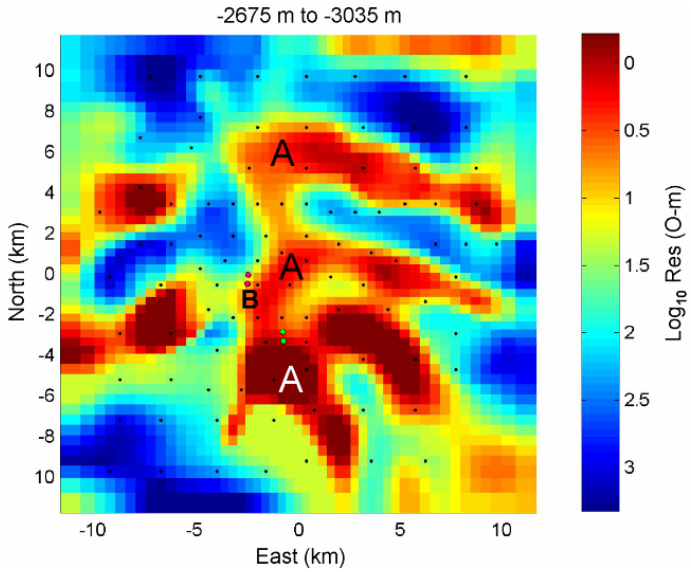


after J. Faulds

⇧ 3D structural perspective view from mapping and wells; ^{3}He R/Ra in production wells

⇦ Purging sample port on well 36-10 for He sampling (L. Owens, Ormat)

- 3D MT confirms 2D recon
- Connection of prod. to depth
- NW-SE trends at multi-scale



3D MT Resistivity Plan View
B is production, A is deep regional

U.S. DOE contract DE-EE0005514

Scientific/Technical Approach

Phase I (Wannamaker et al., 2015, GRC):

- Could only consider existing/no-cost data in defining promising play areas.
- Geophysics/Geology/Geochemistry indicators pointed to Crater Knoll (CK) and Twin Peaks (TP) areas. Also northward from Cove Fort (CF) through Dog Valley (DV).

Phase II:

- Task 1: MT Imaging- MT data fill-in west of Cove Fort toward Twin Peaks, fill some holes in coverage, extend somewhat south. Contracted to Quantec Geoscience, inversion images via in-house finite element platform developed under DOE support.
- Task 2: Passive Seismology - Investigate earthquake swarm and non-swarm clustering through dedicated Nodal passive seismic array deployment (Crater Knoll/Twin Peaks).
- Task 3: Structural Geology - New analysis through high-res DEM and in-field followup guided by geophysics. Siliceous sinter to be dated for age constraints and cross-cutting relationships.
- Task 4: Geochemistry - Geochemistry, heat flow, and geological modeling to constrain circulation volumes and verify geophysical indicators. Passive ^{3}He soil gas detectors tested at known and unknown sites. Heat flow updated from >170 industry TG and deep wells.
- Task 5: Play fairway ranking updated on the basis of new data density and integration of passive seismic results.

Technical Accomplishments and Progress

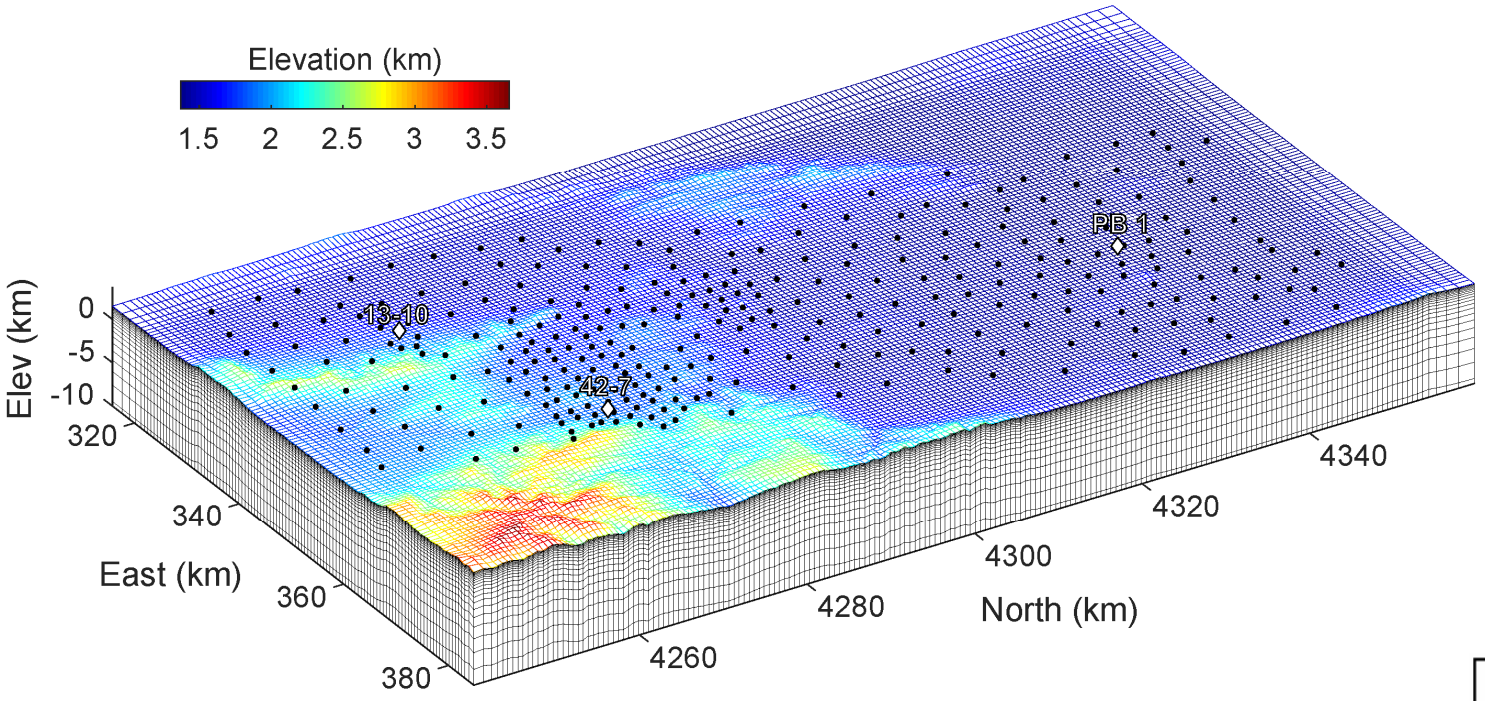
- MT analysis incorporates ultra-remote reference noise abatement, DOE/GPO supported 3D inversion capability.
- Seismic swarm detection utilizes new event template detection methods, state-of-art instrumentation.
- Extensive young siliceous sinter recognized esp. over Twin Peaks area, new mapping conducted/incorporated.
- Passive soil gas 3He detectors not requiring water sampling deployed for first time in geothermal.

Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
MT surveying of TP-CK-CF areas, 3D inversion of integrated data set	Achieved Original	Nov. 2016, Apr. 2017
Nodal seismic array deployments, Event discrimination and location	Achieved Original	Apr. 2017, Jun. 2017
In-field mapping TP-CK, sinter dating, gravity, fault/dilatency quant.	Achieved Original	Oct. 2016, Apr. 2017
Major element geochem review, ^{3}He passive sensor collection	Achieved Original	Oct. 2016, Mar. 2017
Phase II Fairway Play Favorability	Achieved Original	Jun. 2017

U.S. DOE contract DE-EE0002750

Tech A & P

Advances in 3D MT Imaging



< Finite Element Mesh: Sevier Basin/Pioche-Marysvale Belt, Utah

$$\text{Objective:} \quad W_\lambda(m) = \{(d - F[m])^T C_d^{-1}(d - F[m])\} + \lambda\{(m - m_o)^T C_m^{-1}(m - m_o)\}$$

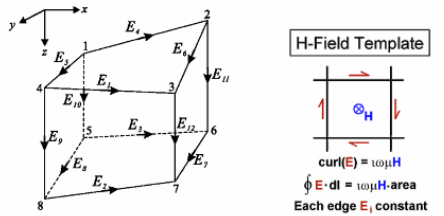
$$\text{NL Step:} \quad m_{k+1} - m_k = \{J_k^T C_d^{-1} J_k + \lambda C_m^{-1}\}^{-1}\{J_k^T C_d^{-1}(d_k - F[m_k]) - \lambda C_m^{-1}(m_k - m_o)\}$$

Stabilized Iterative Earth Resistivity Voxel Estimation
Non-Linear Model Step Recast to Data-Space Formulation
Direct Matrix Solutions Used Throughout (Pardiso, Plasma)
Can Solve for Tensor Impedance Static Distortions
Parallelized on Large RAM, Single-Box Workstations

$$\nabla \times E = -i\omega\mu H \qquad \nabla \times H = \hat{\sigma} E$$

$$\nabla \times \frac{1}{\mu} \nabla \times E - i\omega\hat{\sigma} E = J^{imp}$$

$$E = \sum_{i=1}^{n_e} x_i N_i \qquad H = \frac{-\nabla \times E}{i\omega}$$



EM Field (Maxwell) Equations
And Deformed Finite Element

3D MT Inversion Using Deformable Edge Finite Element Algorithm
(Kordy, Wannamaker, et al., 2016, GJI)

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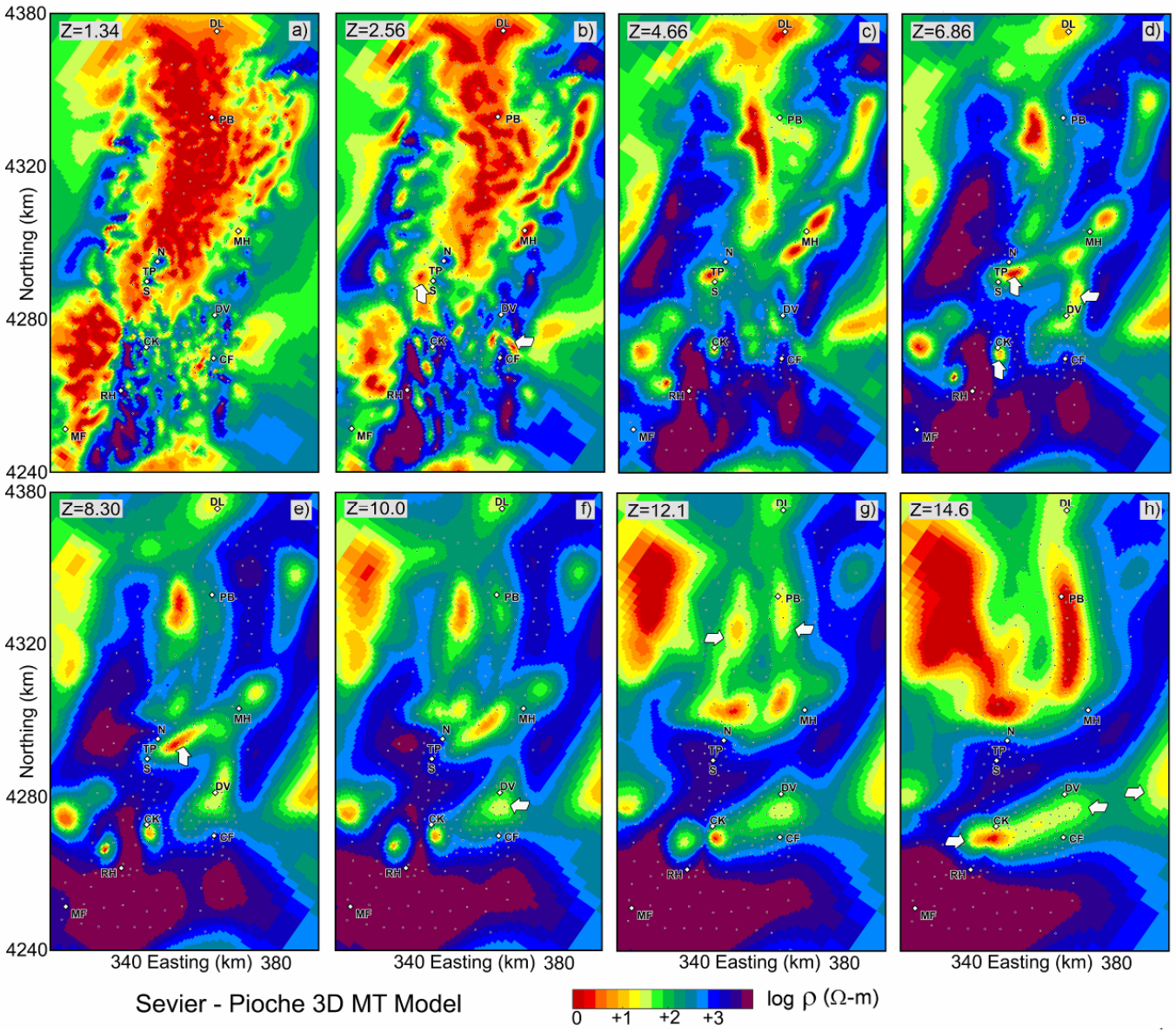
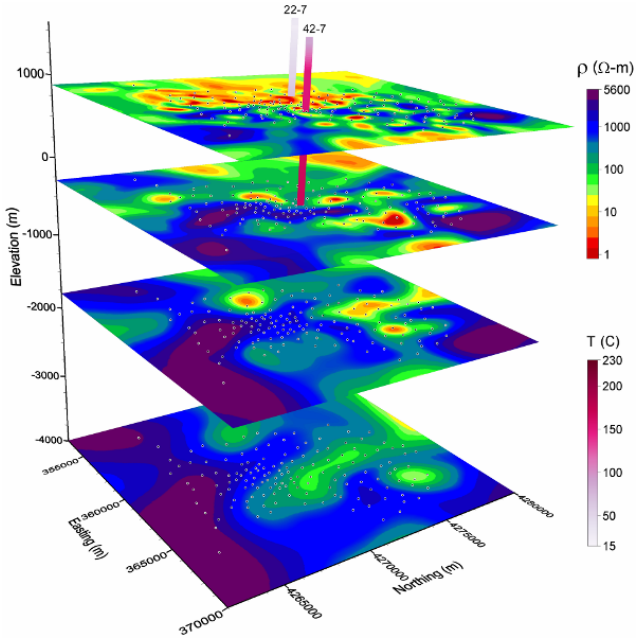




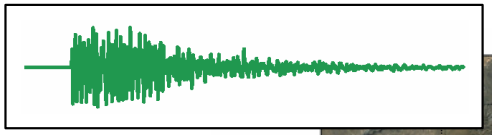
Cove Fort Detailed Model (ENEL focused MT data set) Midcrustal conductive upwelling resolved with better sampling

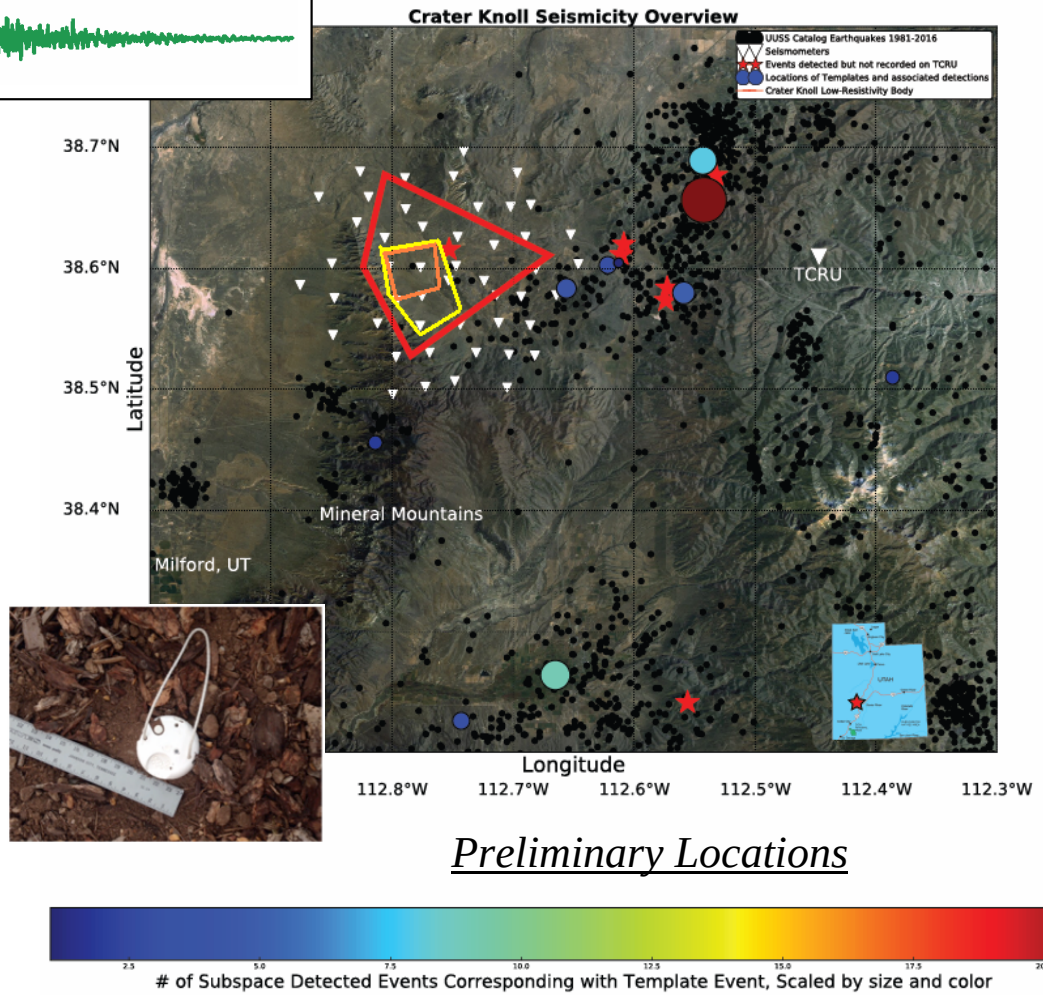
Task 1: Sevier Basin 3D MT Inversion Model: Plan Views to Depth

- Pronounced change across Cove Fort TZ from Sevier Basin onto Pioche-Marysvale plutonic belt
- Localized conductive upwellings: Twin Peaks (TP), Cove Fort (CF), Crater Knoll (CK), Pavant Bt (PB)
- Prominent WSW-ESE lineaments at deeper levels link individual occurences (TP-MH, CF-CK)

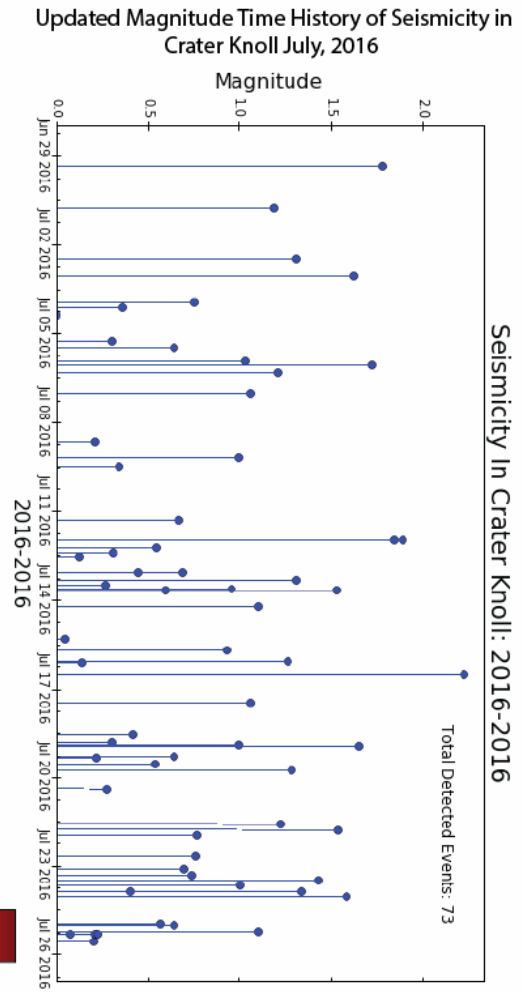
Tech A & P

Nodal Deployment, July, 2016



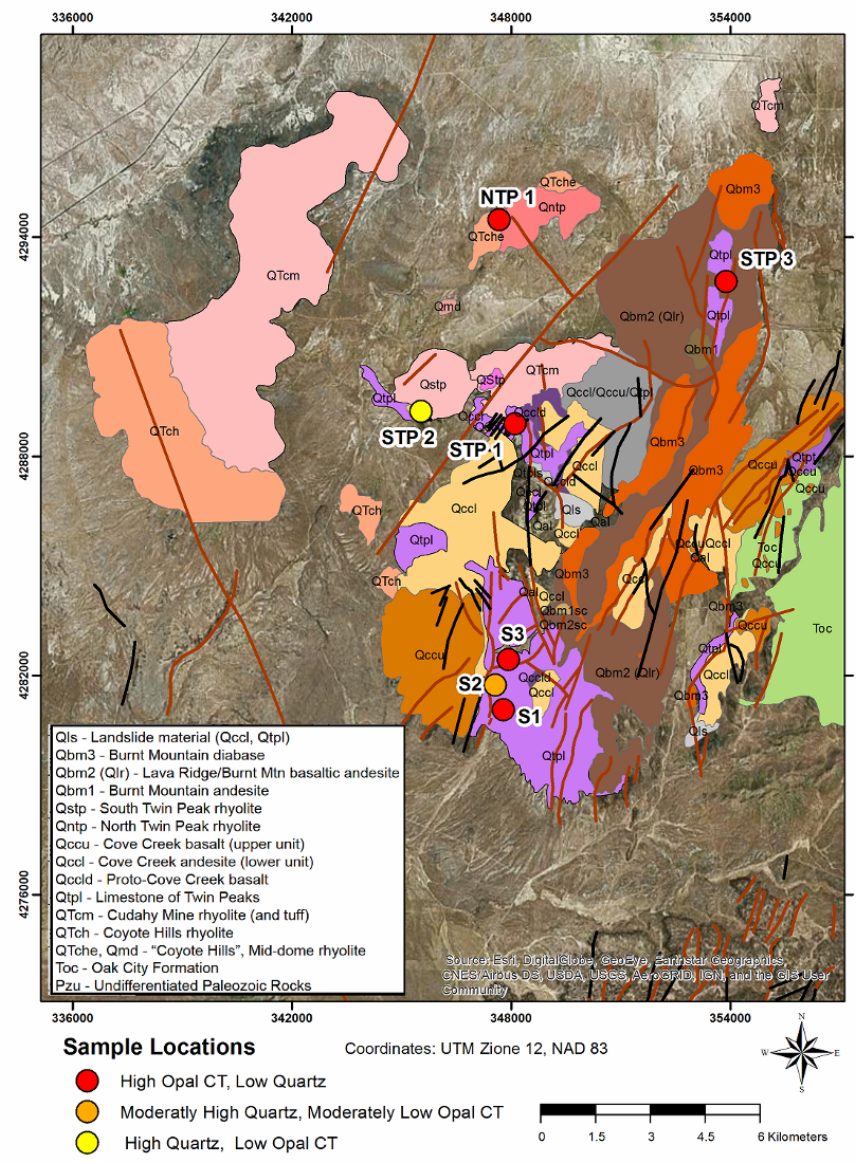


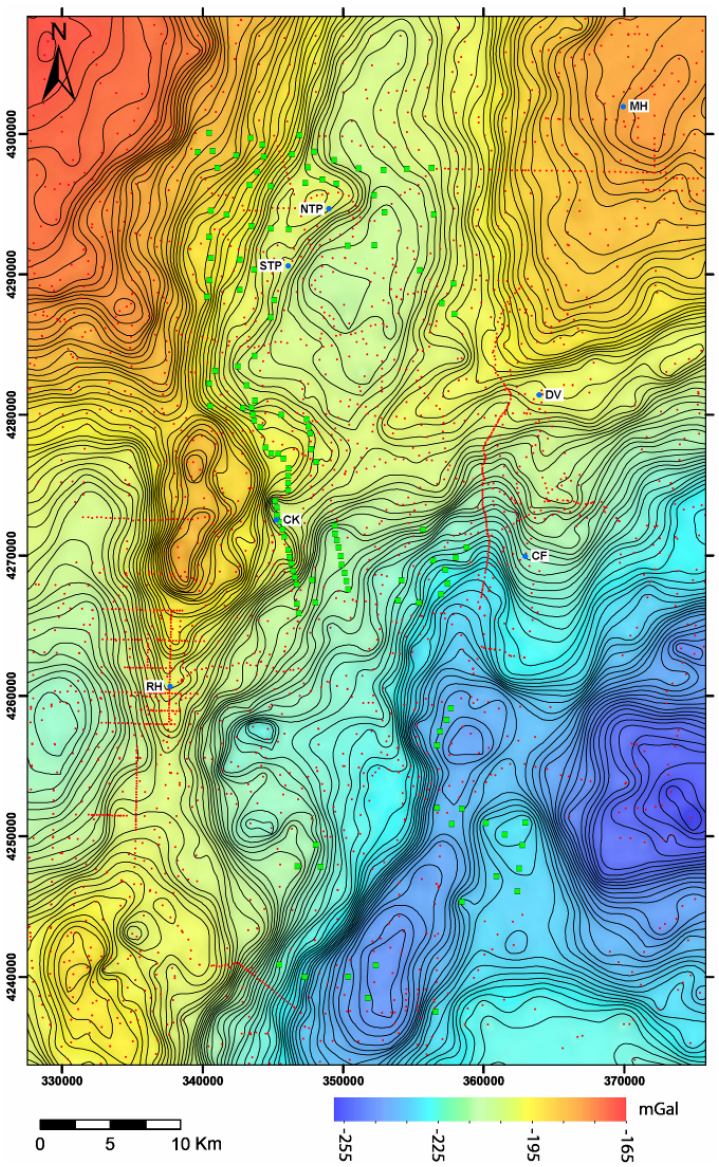
Seismic record, April, 2017



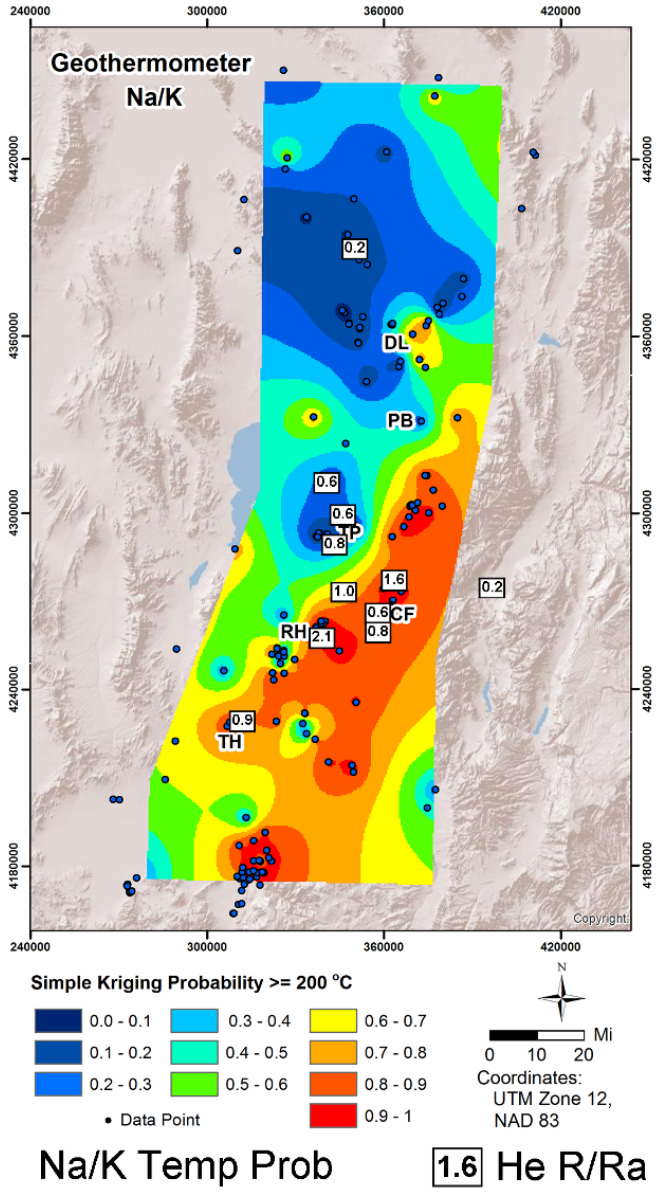
Preliminary Locations

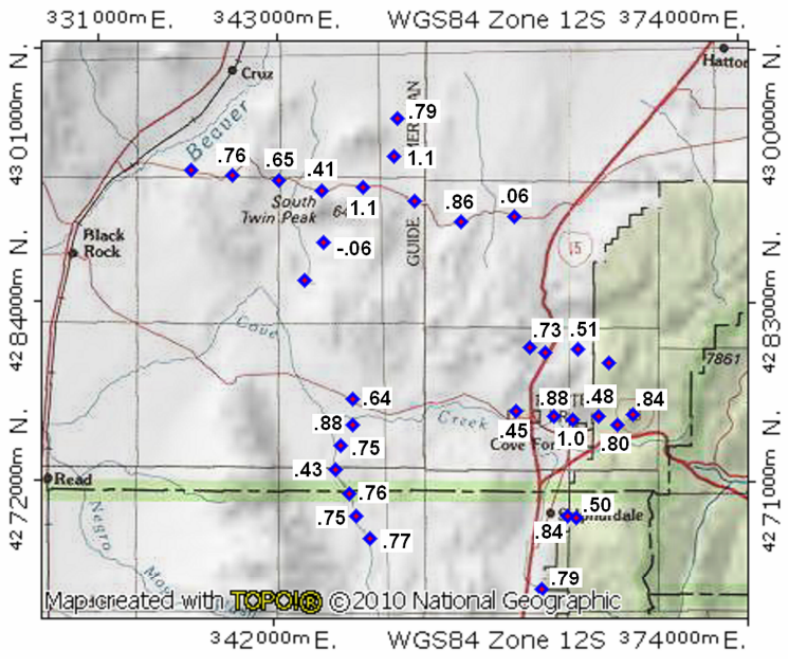
Task 2: Passive Seismology: Nodal seismic instruments emplaced at 43 (net) locations over Crater Knoll MT upwelling area. Sixteen events initially identified, used to create subspace templates. Templating including site TCRU then revealed 73 events over the 30 day period. With locations via first arrivals, majority are associated with Dog Valley area, not Crater Knoll. Possible that three swarms occupy July 12-14, July 19-20, and July 25-26, but this is being further investigated. Similar results obtained from deployment and analysis of Twin Peaks Nodal array, May, 2017.





<u>Task 3: Structural Geology:</u> X-ray d.a. of TP rhyolite siliceous sinter shows Opal-CT dominant, so samples as young as 10 kyr may be present. Hydrothermal petrographic textures.
No new fault structures observed in Google Earth imagery in Crater Knoll area.
Gravity valuable for refining B&R fault offsets under cover, structural intersections





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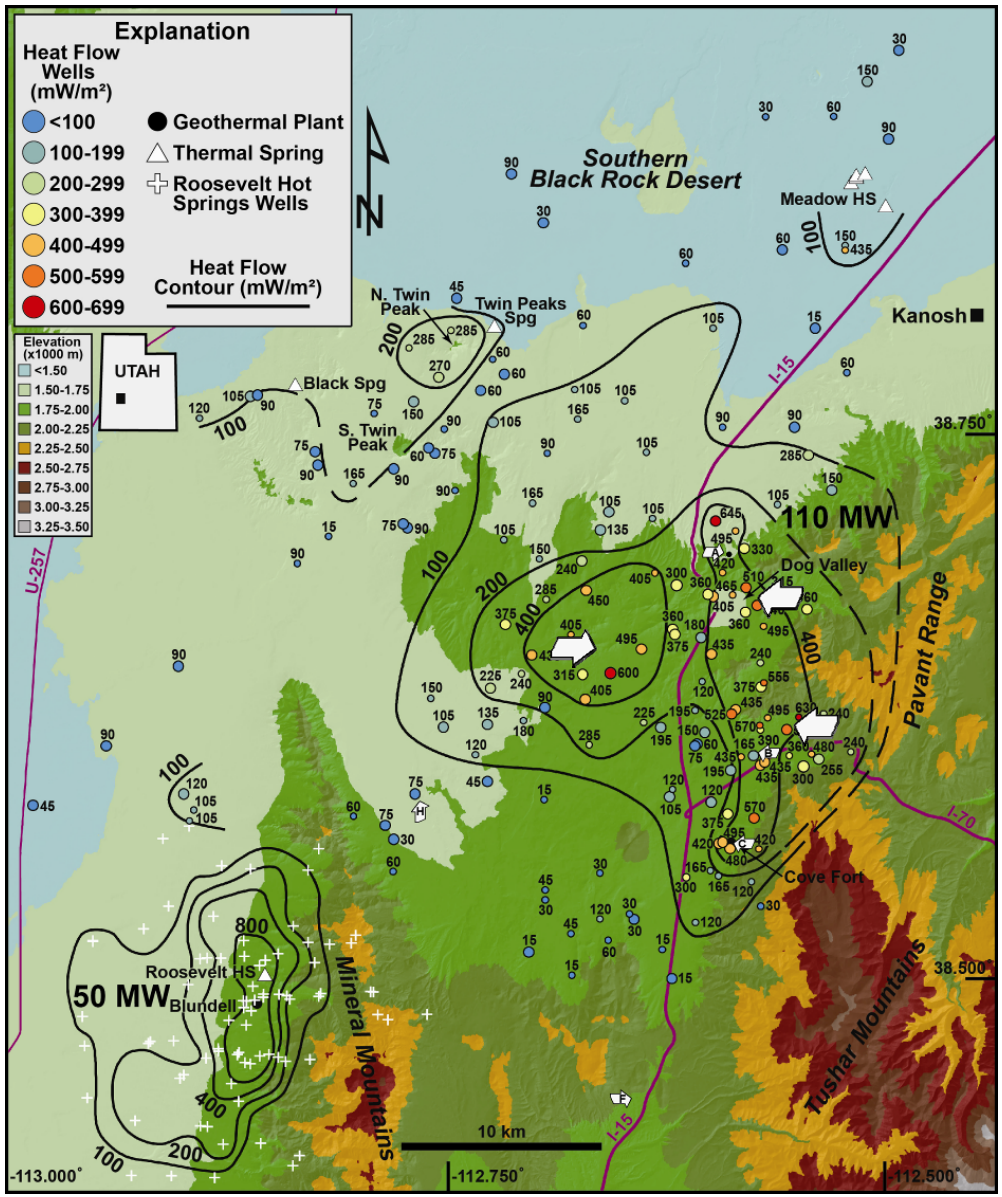
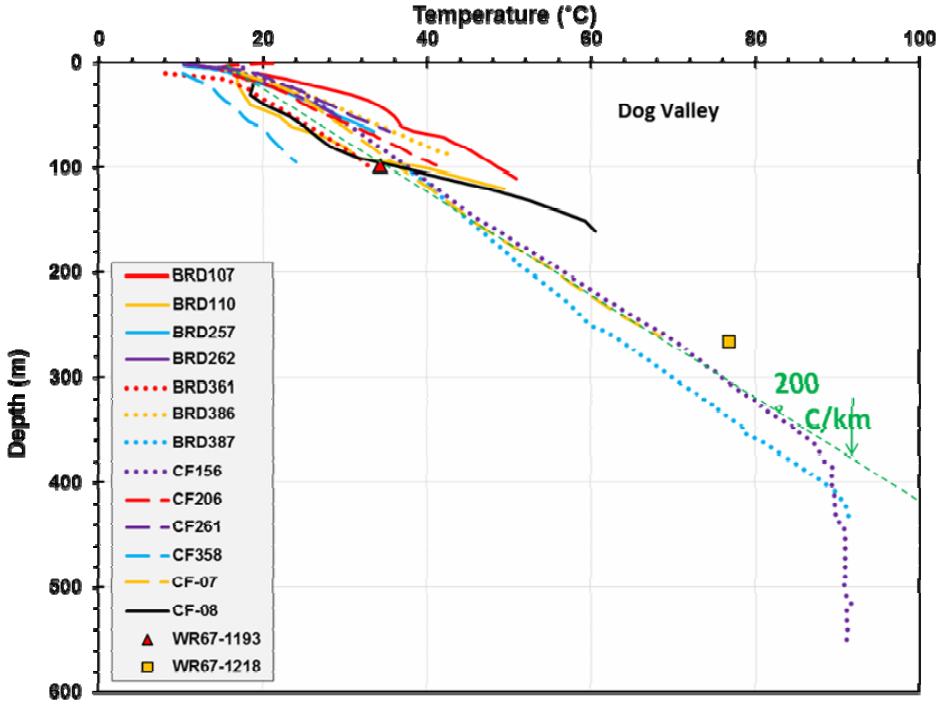
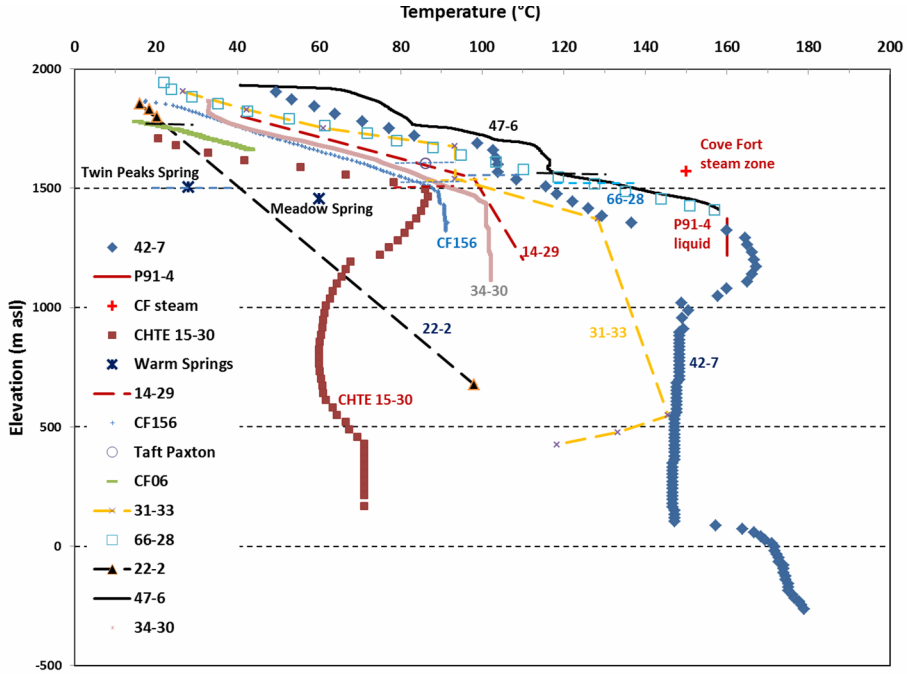
Task 4 (Geochemistry and Thermal Regime):

Left: Coherent band of high Na/K temps connecting Thermo, Roosevelt, Cove Fort. Na/K temp at Cove Fort of ~250 C. Fluids are Cl dominated despite carbonate reservoir. Spring and well fluid samples reveal significant ^{3}He presence, incl. northern Cove Fort.

Above Right: We expand coverage using new diffusive soil gas ^{3}He samplers.







Heat Flow Field over central PFA area

(Allis et al., 2017, SGW)

Strong N-S band north from Cove Fort - Dog Valley

Curious lobe to west of Dog V in Paleozoic section

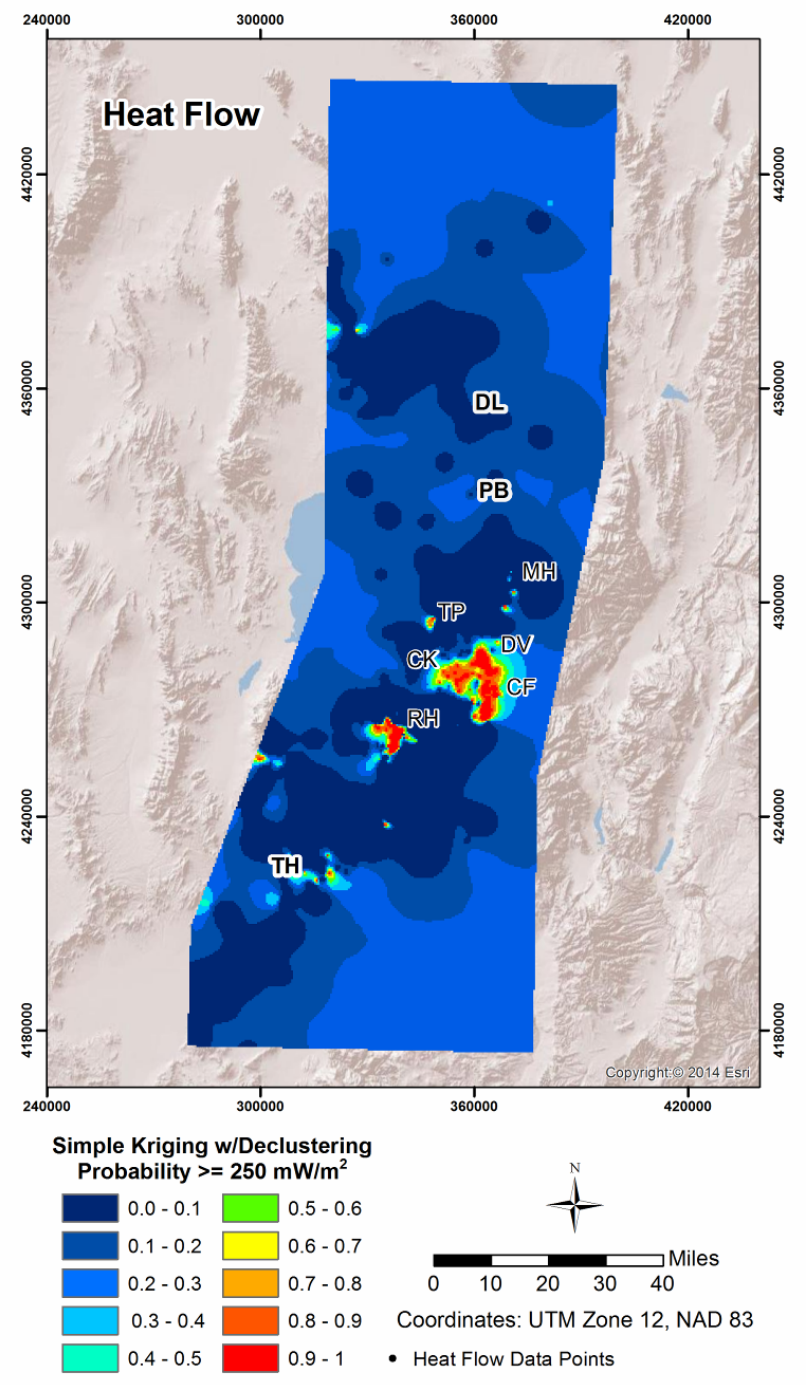
Modest heat flow high by Twin Peaks, poorly sampled

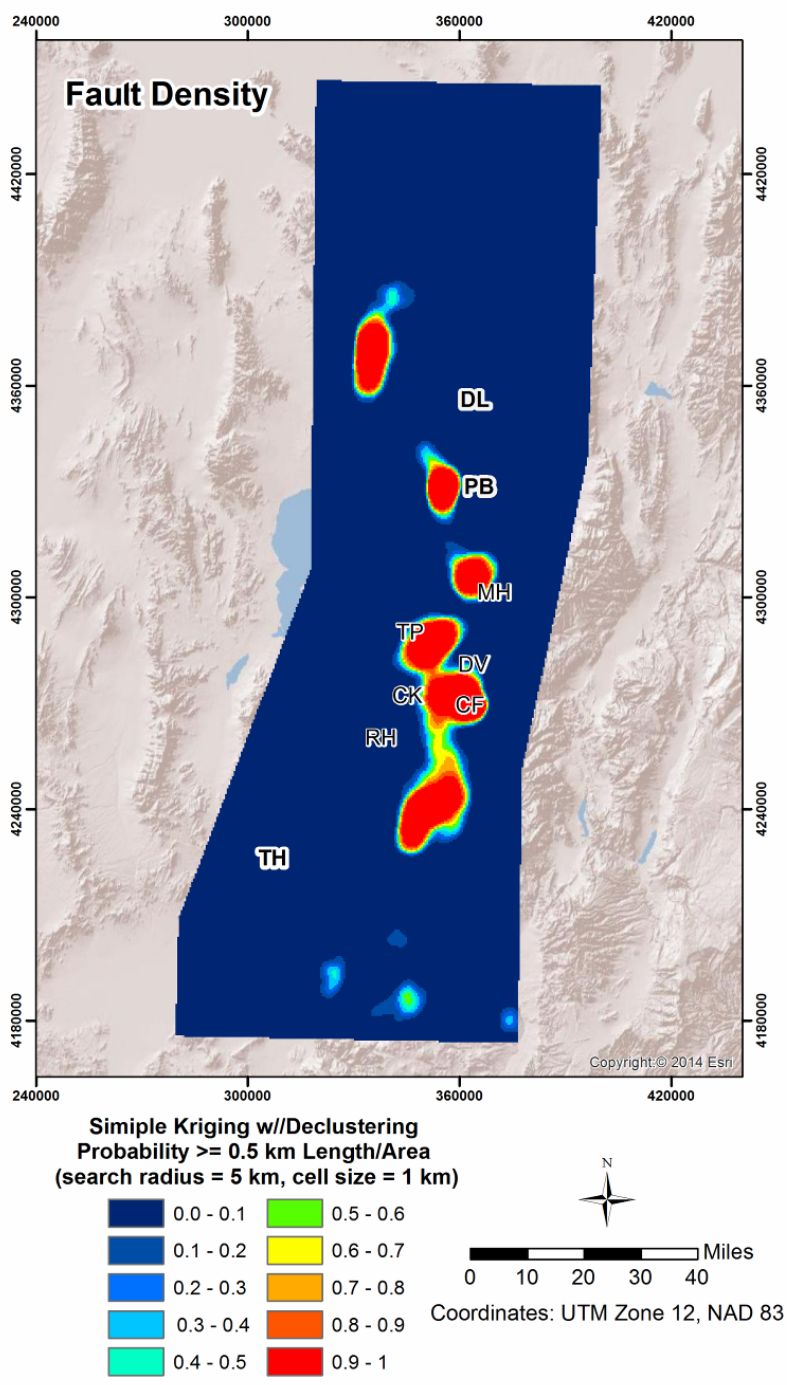
Task 4 (cont'd)

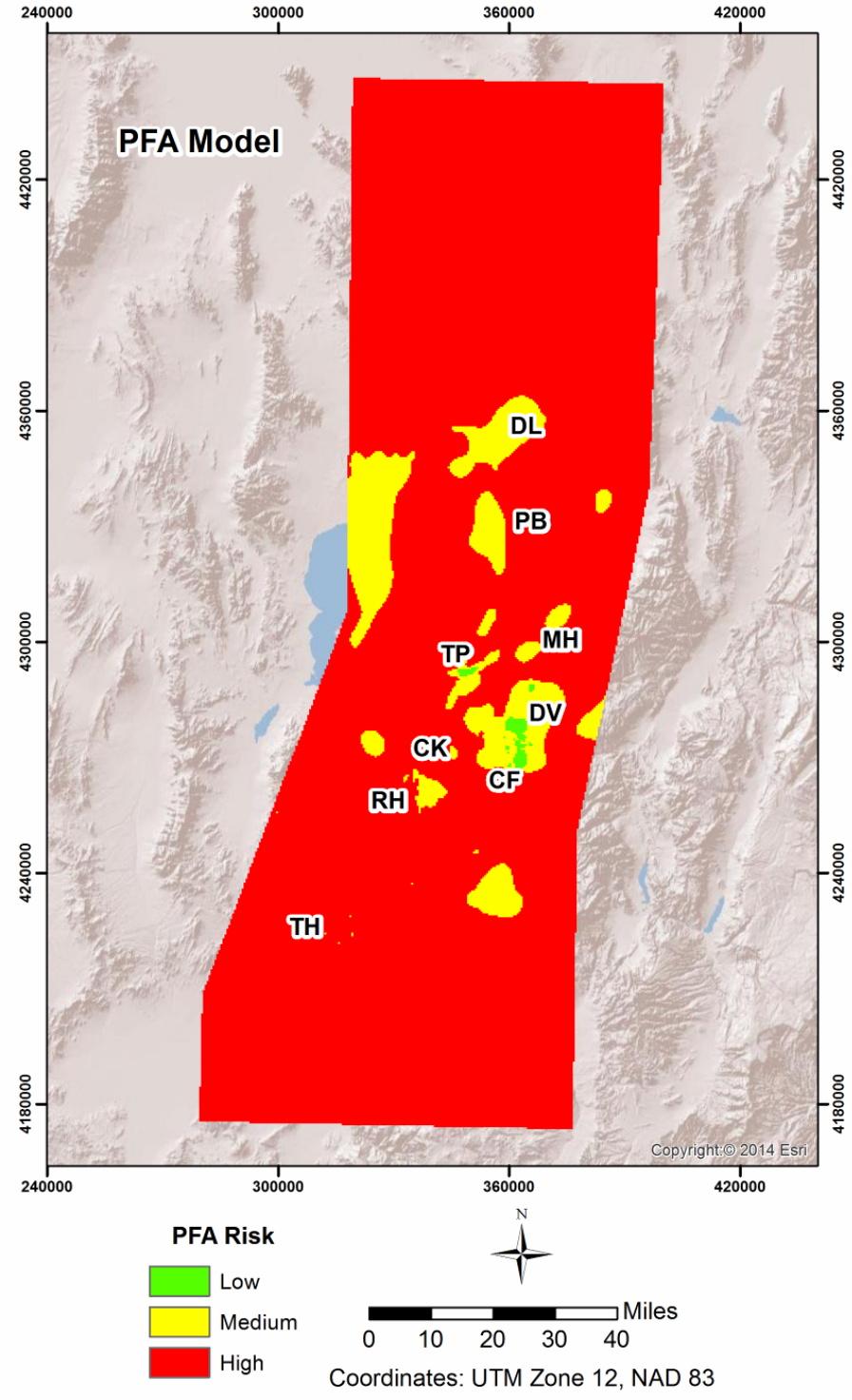
Tech A & P

Task 5: Updated Kriged Probability in Eastern Great Basin PFA Area

Tech A & P







Phase II PFA Summary for Eastern Great Basin

Tech A & P

- Eastern Great Basin remains with high geothermal potential: active rifting, magmatism, good reservoir rocks, dilatent structures, geophysical/geochemical indicators.
- Integration of MT resistivity, gravity, structural analysis and fluid/gas geochemistry have focused exploration plays.
- Low-resistivity upwellings proposed to equate to shallower high temperatures and fluids have been refined through new data coverage, still show control by large-scale WSW-ENE lineaments.
- Twin Peaks and Crater Knoll AOIs are seismically quiet; seismicity and clustering concentrated in Cove Fort – Dog Valley. Some observed at Roosevelt also in FORGE effort.
- Abundant, apparently young siliceous sinter over Twin Peaks area supports hydrothermal activity. Strong fault offsets seen with TP, CK, CF-DV areas.
- Elevated He R/Ra is pervasive over central study area; research still needed on scale of sampling to resolve geothermal targets.
- Northern Cove Fort – Dog Valley and Twin Peaks areas highest priorities. Complex, multi-level hydrothermal regime must be penetrated to resolve geothermal targets.

Research Collaboration and Technology Transfer

- Project is joint effort between Energy & Geoscience Inst. and Dept. of Geology & Geophysics, University of Utah.
- Subcontracts to Utah Geological Survey, and Quantec Geoscience Inc.
- Several students and post-doc funded under the project.
- Long-standing data acquisition and processing relationship with subcontractor Quantec Geoscience.
- PI Wannamaker advises subcontractor on field setup (e.g., ultra-remote referencing) and response processing in areas of widespread cultural/industrial EM interference.
- Progress and results presented multiple times per year at geothermal/exploration conferences attended by industry, academia and national labs.

Future Directions

- Phase II activities ended September, 2017.
- Phase III funding and activities to commence October, 2017, lasting 18 mo.
  - DOE/TMT/UU-PFA teams agreed to emphasize N Cove Fort-Dog Valley area for follow-up data collection and test drilling.
  - Two 2-3000 ft air-drilled holes to be carried out by USGS.

Ph III Milestone or Go/No-Go	Status & Expected Completion Date
1. Concentrated MT Surveying CF-DV	Completed Oct. 2017, Interp. Mar. 2018
2. Dedicated Seismic Nodal Arrays CF-DV	Installed Oct. 2017, Interp. Jun. 2018
3. Structural Geology/Gravity	Field work Oct. 2017, Interp. Jun. 2018
4a. CO2-3He Geochemistry	Field work Mar. 2018, Interp. Jun 2018
4b. Geological Modeling/PFA Update	Expected Aug. 2018
5a. Thermal regime/fluid drill hole 1- N CF	Expected Oct. 2018
Go/NoGo: Outcome of drillhole 1- N CF	Determine Dec. 2018
5b. Thermal regime/fluid drill hole 2- DV/AV	Expected Oct. 2018
6. Reporting/Market Transformation	Contin. at GRC, SGP; Data archived with GDR

Summary

- Eastern Great Basin should have high geothermal potential given active rifting, magmatism, good reservoir rocks, dilatent structures.
- Integration of MT resistivity, structural analysis and fluid geochemistry constitutes methodology for prioritizing exploration and play ranking.
- Low-resistivity upwellings resolved using new MT inversion capability may equate to shallower high temperatures and fluids.
- New seismic clustering and waveform correlation techniques have been tested, promise to improve swarm detectability and reliability significantly.
- Numerous favorable structural settings identified from mapping and geo-morphology.
- Advancing methods of passive geochemical isotope surveying as additional evidence of high-T fluid presence.
- Test wells target subsurface temperatures of ~150 C to test PFA methodology and expand resource indications.